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Metal Enrichment of Ly alpha Clouds and Intergalactic Medium

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Abstract. We have examined the metal enrichment of the intergalactic medium (IGM) based on a galactic wind model. A galactic wind driven by supernovae brings metallic gas to the IGM but not so far beyond the gravitational potential. The expanding velocity of the outflow depends on the star formation timescale. Examining 3D calculation for the IGM in CDM model, we find that only 10 % region has metallicity larger than $10^{-2}Z_\odot$ at $z = 3$. Wide range of the IGM metallicity produces variety of CIV column densities for a fixed HI column density.

1 Introduction

Recent observations have shown us that many Ly α clouds are contaminated with metals. Associated CIV absorption lines indicate that these clouds are likely to have about 1/100 solar metallicity [7], [3], [6]. This puzzles us how such intergalactic clouds are metal-enriched, since metals must be synthesized in stars, i.e. in galaxies. Another question is whether Ly α clouds with lower HI column densities are metal-enriched or not.

In this work we examine galactic wind driven by supernova explosions to provide metals to the IGM, in order to find answers for above questions.

2 MODELS

We have examined three models to investigate how a galactic wind propagate and bring metallic gas to the IGM on the minihalo model: a spherical cloud model, a grid toy model, and a 3D CDM model.

Assumptions over these models are summarized as follows: Gas and dark matter are in a flat universe ($\Omega = 1$) with $H_0 = 50$km s^{-1}Mpc^{-1} ($h = 0.5$). Stars are formed at high density and low temperature region. Eleven percent of stars in mass become supernovae with releasing 10^{51}erg and $3.2M_\odot$ metallic gas per an average supernova which mass is $20.5M_\odot$. Uniform UV background radiation is assumed with power-law spectrum of $\alpha = 1$. The flux evolution model is assumed similarly to Haardt & Madau's model [5] and $J_{21} = 0.72$ at $z = 3$, where $J_{21} = J(912\text{Å})/10^{-21}$erg s^{-1}cm^{-2}Hz^{-1}str^{-1}. For the spherical model the constant flux model with $J_{21} = 1$ is also considered. This will change the formation epoch of stars. Ionization equilibrium is assumed, and radiative cooling and UV heating are taken into account.

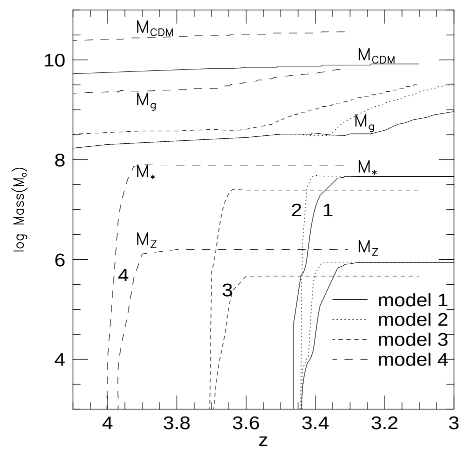

Figure 1: Redshift evolution of metallic gas mass(M_Z), stellar mass (M_*), gas mass(M_g), and CDM mass (M_{CDM}) for model 1 ($J_{21} = 1$, $\tau_{SF} = 3 \times 10^7$yr, $r_c = 90$kpc), model 2 ($J_{21} = 1$, $\tau_{SF} = 10^7$yr, $r_c = 90$kpc), model 3 ($J_{21} \sim 0.7$, $\tau_{SF} = 10^7$yr, $r_c = 90$kpc), and model 4 ($J_{21} \sim 0.7$, $\tau_{SF} = 10^7$yr, $r_c = 150$kpc), where r_c is the core radius of the CDM distribution. The gas mass increases because the expanding shell sweeps the IGM.

2.1 Spherical cloud model

First we examine propagation of a galactic wind from a minihalo with a simple spherical model. A system of dark matter and gas ($\Omega_b = 0.1$) evolves from a Gaussian density fluctuation [1]. Star formation criterion is set as $\rho_b > 1.67 \times 10^{-24}$g cm^{-3}, and $T < 10^4$K. Stars are formed with the timescale, τ_{SF}.

An expanding shell due to supernova explosions propagates into the expanding region, being accumulated all gas which is collapsing onto the minihalo. The expansion is accelerated by the pressure gradient. The expanding velocity of the shell when it is propagating into the IGM region is $V_{exp} \simeq 150 - 300$km/s ($\tau_{SF} = 10^7 - 3 \times 10^7$yr). In this spherical model the metallic gas is confined in the hot cavity region. When τ_{SF} is long such as 10^8yr, supernovae do not produce an expanding shell. Lasting period of the star formation is short $\sim (3-4)\tau_{SF}$. The stellar component ($M_* \lesssim (0.03 - 0.05) M_g$) distributes at $R_* \lesssim 3 - 10$ kpc (depending on the initial density fluctuation). Average metallicity of the system is $Z = M_Z/M_g \simeq 0.06 - 0.005 Z_\odot$ at $z \sim 3$.

2.2 Grid geometry model

To examine how metals expand in a space where voids (low density region) and gas sheets or wall (high density region) exist, we consider a toy model with grid geometry of walls and voids. Here we consider a $2h^{-1}$ Mpc box (comoving)

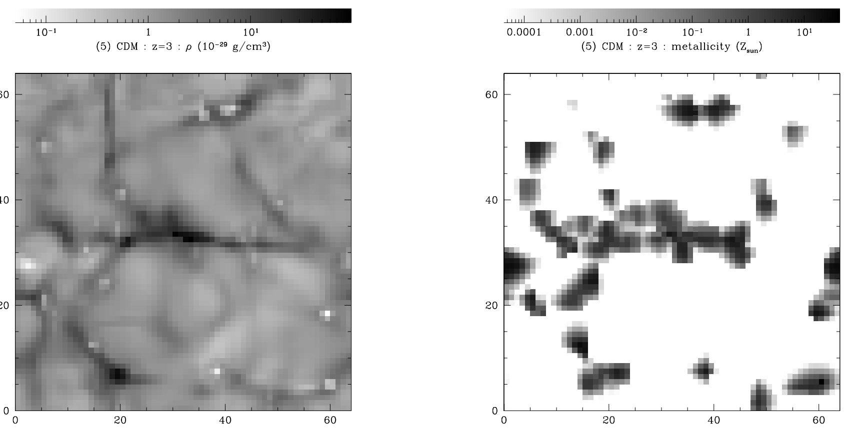

Figure 2: Snapshot of the gas density distribution (left) and the metallicity distribution (right) at $z = 3$ in 3D IGM model.

with 64^3 mesh and 64^3 CDM particles. Walls separate 8 void regions in the simulation box. The void under-density is assumed as $\delta\rho_V = 0.80$ and the wall over-density, $\delta\rho_W = 1.62$. The wall width is put as $0.25h^{-1}$ Mpc. A galaxy ($M_* = 5 \times 10^{10} M_\odot$) which is put near the center has supernova explosions at $z = 4$ to spread out metallic gas into the IGM.

Shocked hot gas shell following cool and dense gas shell expands in the IGM. The wall prevents the shell expansion which propagates toward the voids with the expanding velocity, $\sim$ 200km/s, at $z = 2.75$. Most metallic gas is accumulated in the dense shell, where CIV number density is high as well as HI number density. The unperturbed walls are not metal enriched. The IGM metallicity is almost uniform from the central region to the dense shell. Beyond the shell the metallicity decreases with decreasing gas density.

2.3 3D IGM model in CDM model

We have performed 3D simulations in the CDM model to examine metal distribution of the IGM. We take a $20h^{-1}$Mpc (comoving) box with 64^3 mesh and 64^3 CDM particles. We assume $\Omega_b = 0.052$, and $\sigma_8 = 1.01$ for the CDM model. Galaxies are assumed to form at a cell where $\rho_{tot} > 5\rho_{crit}$, $\rho_b > \bar{\rho}_b$, $\nabla \boldsymbol{v} < 0$, and $T < 2 \times 10^5$K, and all gas in the cell is converted to stars. (e.g. [2].) Supernovae are assumed to explode soon after galaxies are formed.

First we find that supernova feedback acts to suppress galaxy formation near galaxies. The galaxy formation rate (mass per unit redshift) becomes nearly constant at $z < 10$, contrary to a model without supernova feedback, which rate show a peak around $z \sim 6$.

The IGM is heated by supernovae during $z \approx 5-12$, and by gravitational collapse at $z \lesssim 5$, in average. The metallicity distribution mostly traces the high density regions where galaxies are formed and metals are produced. Some low density regions caused by galactic winds and bulk motion are found to have high metallicity. The metallicity is less than $1/100\ Z_\odot$ at more than 90 % region at $z = 3$. Supernova explosions produce two trends in plots of the metallicity vs. the gas density. The metallicity keeps high near galaxies with wide range of the gas density. On the other hand, expanding gas towards void regions makes a trend of lower metallicity with lower density. These trends are clearly seen in the toy grid model in §2.2 and were not found by models without supernova feedback [4]. The CIV column density, N(CIV), spreads widely for a fixed HI column density, because of wide range of the metallicity. At $z = 3$ all $10^{15} \leq$ N(HI)$< 10^{17}$cm^{-2} clouds seem to have N(CIV)$\geq 10^{12}$cm^{-2}, similarly to observations [6].

3 DISCUSSION

The results of these models show that: (1) galactic winds from minihalos and galaxies carry metallic gas to the IGM but are not powerful enough to pollute all the IGM. Even at $z = 0$ only 30 % region has metallicity larger than $10^{-2} Z_\odot$; and (2) CIV absorption lines would be associated at high density regions. The CIV column densities and metallicity are likely to show similar tendency to the observations.

These models are still preliminary and we need more improvements. For example, simulations with higher spatial resolution would make a change of galaxy formation rate, because the formation criterion might allow to form more galaxies but increased number of supernovae would prevent succeeding formation of galaxies. The change of the galaxy formation rate will affect the precise metallicity distribution. Improved models are being planed to examine, which will give us more realistic information on the metallicity of the IGM.

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